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On The Intrinsic Flexibility of the Double Skin Façade: A Comparative Thermal Comfort Investigation in Tropical and Temperate Climates

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Abstract

Double Skin Façades (DSFs) are applied in both new and existing buildings, and most of such applications are found in temperate climates. Although research in this area is growing steadily, comparative analyses of DSF applications in different climates are still few and far between. This paper addresses such a gap by means of a comparative thermal comfort analysis of a DSF building model in both tropical and temperate climates. London and Rio de Janeiro have been selected as two representative cities, and three building orientations in each city have been considered; S, SW, and SE, for London in northern hemisphere and N, NW, and NE for Rio in southern hemisphere. Dynamic building energy modelling has been used to determine and assess indoor environmental conditions. While IES VE as the main software tool was utilised, the accuracy and reliability of the results were also cross-checked against a computational fluid dynamic (CFD) software package. Thermal comfort has been assessed through the adaptive comfort approach and results have been analysed and presented in form of comfortable indoor conditions during occupied hours. Results of this study show that the intrinsic flexibility of the DSF can offer indoor comfort for more than half of a year in both climates without any need for mechanical heating/cooling, which contributes significantly to reducing energy demands and cutting CO₂ emissions. Additionally, the study shows that the wind force plays a dominant role in driving airstreams in and through the DSF, which highly impacts the overall thermal performance of the buildings. Findings from this research can be useful to academics and practitioners alike, to inform better DSF design and to shed light onto further avenues for DSF research.

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1. Introduction

Around half of the energy consumption, greenhouse gas (GHG) emissions and depletion of natural resources worldwide are believed to be down to construction sector [1]. Without a resolute and concerted effort, carbon dioxide (CO₂) emissions related to worldwide energy consumption will double by 2050 [2]. Although much can be done by maximising the share of sustainable and renewable sources, the role of reduction in energy demand cannot be overlooked [3]. It is of paramount importance for the construction sector, to reduce its energy demand while also ‘greening’ its energy supply through maximising the use of renewable energy and passive strategies. In fact, the need of realising more efficient buildings is holistically called upon for by all future agendas. Given this context and the flexibility that Double Skin Façades (DSFs) can offer in design, they can provide significant benefits in reducing both heating and cooling loads of the buildings to which they are applied [4]. A DSF consists of an internal layer and an additional, usually glazed, external skin, separated by an air cavity that may either act as a thermal buffer zone, as a

ventilation channel or, more often, as a combination of the two. Additionally, the cavity often incorporates shading devices, such as blinds, to protect the internal rooms from overheating caused by solar gain [5].

Existing literatures on DSF cover a broad range of different aspects, such as shading elements in the cavity [6–9], airflow analysis and prediction [10–13], fire and smoke spreading issues [14–17], operational and embodied energy [18, 19] and natural ventilation [5, 20–22]. Natural ventilation is of paramount importance for the operational behaviour of the façade and, in this respect, the surrounding climate plays a crucial role in determining the DSF's effectiveness [23–25]. Recent reviews [26] have shown that our understanding of natural ventilation aspects of DSFs is yet to be fully substantiated, and that the cavity is often considered as an 'isolated' structure and treated as a local thermal feature without taking into account its influence on and exchanges with the spaces.

Furthermore, research on DSF is generally focused on single climatic zones [e.g. 27], if not a single season within a single climate [e.g. 23]. Although one might argue that the depth of such an investigation often requires a narrow approach, there is no doubt that the sacrifice of a broader assessment aimed at understanding the potential flexibility of DSF technologies, as a result, is inevitable. Few comparative assessments do exist, but they have either taken an oversimplified approach to building models [28] or have taken such a specialised approach to specific types of DSF that do not represent current practice with the Architecture, Engineering and Construction (AEC) sector (for instance façade equipped with phase change materials (PCM) in the air chamber [29]).

This research aims to fill such a gap in knowledge by means of a comparative thermal comfort analysis of a DSF building model in both tropical and temperate climates. London and Rio de Janeiro have been selected as two representative cities, and three building orientations in each city have been considered; S, SW, and SE, for London in northern hemisphere and N, NW, and NE for Rio in southern hemisphere. The focus is on achieving thermal comfort merely by passive operational strategies (passive heating/cooling) of a DSF. A methodology based on dynamic building energy modelling has been used to determine and assess indoor environmental conditions, and it is presented in the following section.

2. Methodology

Due to the free-running nature of such naturally ventilated buildings the adaptive thermal comfort approach is used for which air temperatures and air velocities are combined together to determine whether or not indoor conditions fall within or outside a comfort range [30, 31]. In this respect, Building Energy and Environmental Modelling (BEEM) software tools are arguably the most effective ways to achieve detailed analyses of buildings, such as those presented in this paper. Furthermore, they represent the only possible approach where the aim is to assess different orientations of a building, with different configurations, in different climates—which is the case of this research. The main software tool used is IES VE, a building thermal simulation calculation engine that can model natural ventilation systems using the airflow network approach. Additionally, a model calibration through a comparison against FLOVENT, a computational fluid dynamics (CFD) software package, is also carried out to assess the accuracy and reliability of the results.

2.1. Climates characterisation

Rio de Janeiro is located on the southeast coast of Brazil (latitude 22.9° S, longitude 43° W). According to the Köppen-Geiger classification, the city has a tropical humid climate, with hot and humid summers (code: Am) [32]. To the contrary, London (latitude 51.5° N, longitude 0.12° W) is characterised by a temperate climate, with warm summers, and without a dry season (code: Cfb) [33]. A detailed analysis of the weather data files highlighted the significant difference that exists between the two climates (Figure 1). Figure 1 shows maximum, minimum, and average monthly temperatures [°C], and monthly average values of direct solar radiation [Wh/m²] of both cities. In Rio de Janeiro, both temperatures and direct solar radiation are constantly high with average annual values of 24 °C and 184 Wh/m²—respectively. London shows a far different scenario: temperature fluctuates much more throughout the year with several months characterised by minimum temperatures below 0 °C. Yearly average values for temperatures and direct solar radiation are 10.6 °C and 94.9 Wh/m²—respectively.

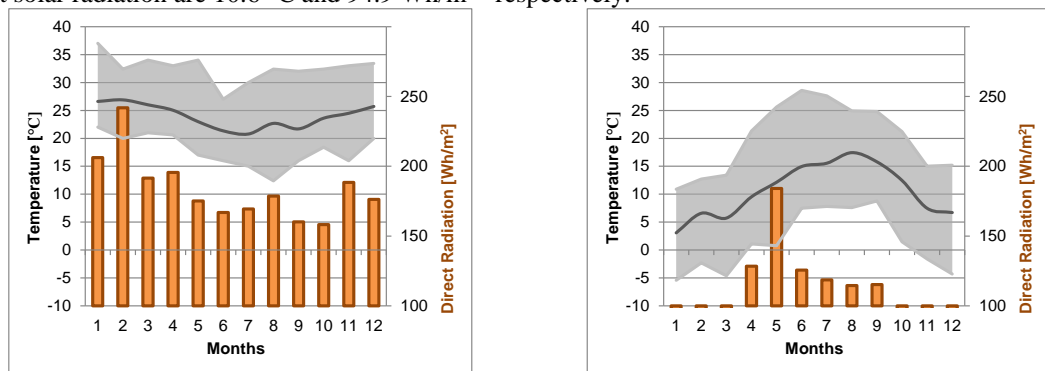


Figure 1 - Climate characterisation for Rio de Janeiro (left) and London (right)

Two main forces drive the airflow in the cavity of a naturally ventilated DSF, i.e.:

- Pressure differences caused by solar-induced thermal buoyancy
- Pressure differences caused directly by wind action

For the former, outside air temperature, temperature gradient within the cavity, and solar radiation all play important roles. In fact, solar radiation is transmitted through the outer glazing of the DSF, warming up the air in the cavity. As the cavity is connected to cooler external air via openings at the top and the bottom, a process of pressure equalisation tends to occur and the warmer and lighter air moves towards the top of the façade. In case of the latter, wind velocity, wind direction, openings height, and orientation of the building are all important elements. Figure 2 shows the wind rose for each city and the six different orientations of the DSF that have been considered (N, NE, NW for Rio de Janeiro, and S, SW, SE for London).

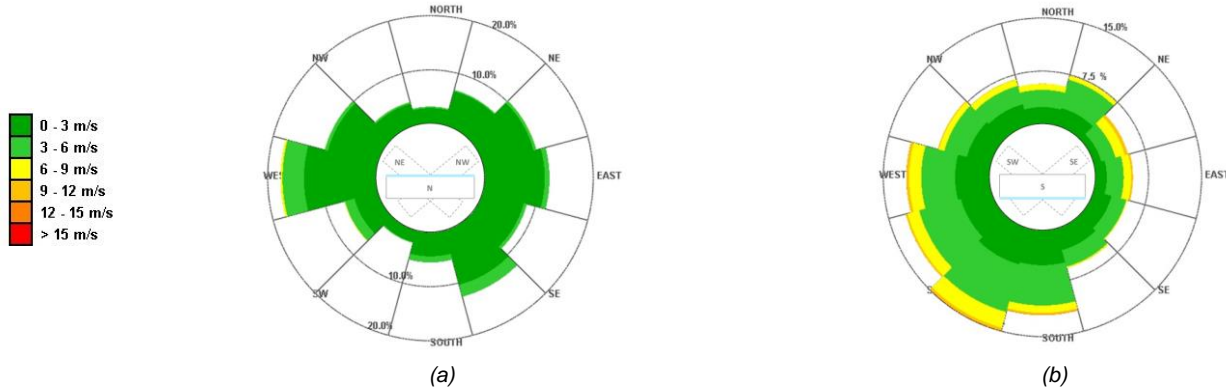


Figure 2 - Wind Rose and orientations of the different scenarios considered for (a) Rio de Janeiro and (b) London

A climate diagnosis of the two cities has been conducted through psychrometric chart analyses obtained through ‘Analysis Bio’, an application developed at the Federal University of Santa Catarina in Brazil to help plot psychrometric charts [34].

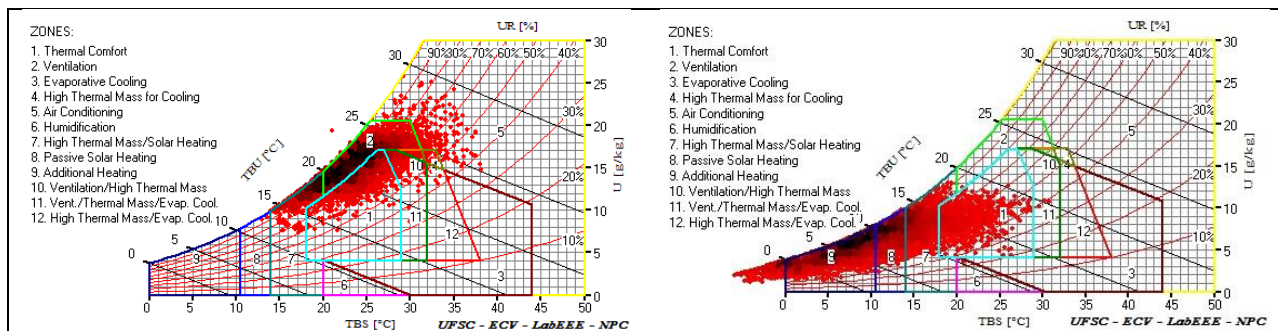


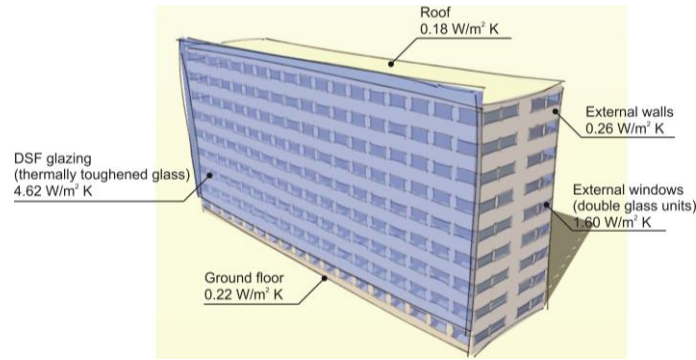
Figure 3 - Psychrometric charts for (a) Rio de Janeiro and (b) London

For Rio de Janeiro the analysis shows that, although mechanical cooling is undoubtedly necessary over summer, one of the main passive strategies recommended is natural ventilation, which can offer thermally comfortable conditions for up to 61% of a year. In London, the psychrometric chart shows that passive solar heating can be successfully deployed for up to 38% of the year, providing that additional heating is in place in the coldest periods.

2.2. Model characterisation

The developed model for this study is a medium- to high-rise office building, with a very slender built form, which consists of 9 storeys measuring at 66.6m long by 16m wide totalling at 9590 m² of treated floor area (TFA). The building is a generic type yet representative of medium- to high-rise offices in both Rio de Janeiro and London as they are large centres of population that often accommodate offices of such kind. Table 1 presents an axonometric view of the building model, and heat transfer coefficients (U-values) for the principal elements of the building fabric.

Table 1 – Characterisation of the building model



The DSF is a multi-storey type, consisting of a cavity with no horizontal or vertical partitions. Additionally, the cavity extends by 1.5m over the total height of the building in order to guarantee a residual chimney effect and minimise the risk of severe overheating of the upper floors. Although the building is 9-storey high, the results will be shown for 8 floors only as DSF does not apply to the ground floor. The cavity is 1m wide, equipped with shading devices in form of operable light-coloured venetian blinds. The model incorporates a basic form of Building Management System (BMS) that lowers the shading devices when solar radiation reaches a threshold value (300 W/m^2) and opens the bottom and the top of the DSF cavity. In the simulations, the threshold for opening external windows has been set equal to $20 \text{ }^\circ\text{C}$ (Rio de Janeiro) and $22 \text{ }^\circ\text{C}$ (London). The occupancy profile is 8am–6pm, Monday to Friday. Assumptions made in the thermal zoning of the model have been made in accordance to IES VE guidelines, manuals, and knowledge base. In the model, the DSF cavity has been divided into several horizontal zones (one for each floor) each associated with an airflow network node. With this arrangement, fully open orifices connect each cavity zone with the neighbouring ones, and the multi-zone airflow calculations are performed at each time step.

Finally, the building is set as completely free-running; in other words, no heating/cooling system is in place. The rationale behind this choice is the aim to assess to what extent passive strategies for thermal comfort can be exploited merely due to the DSF. It has to be noted that the building is exactly the same, as is the DSF; the only difference lays in how the DSF is managed according to the surrounding environment to best serve the purpose of providing indoor comfort condition with no need for mechanical heating/cooling. Thermal comfort is assessed in terms of comfortable indoor conditions during occupied hours. This assessment is based on the adaptive comfort approach, which relates operative temperature and prevailing mean outdoor temperature. Operative temperature (T_{op}) is obtained from Eq. (1) [35]:

$$T_{op} = \frac{T_a \sqrt{10v} + T_r}{1 + \sqrt{10v}} \quad (1)$$

, where T_a is the indoor air temperature [$^\circ\text{C}$], T_r the mean radiant temperature [$^\circ\text{C}$], and v the air speed [m/s^{-1}].

Prevailing mean outdoor temperature (PMOT) is based on the average of the mean daily outdoor temperature of the previous fifteen days. For what concern upper and lower bounds of the acceptability range (with an 80% acceptability assumption), values are calculated following Eq. (2) and Eq. (3):

$$UB_{80\%} [^\circ\text{C}] = 0.31 \times PMOT + 21.3 \quad (2)$$

$$LB_{80\%} [^\circ\text{C}] = 0.31 \times PMOT + 14.3 \quad (3)$$

3. Code-to-code model calibration

Although energy simulation software is advanced in the treatment of the real-life building energy processes, modelling complex systems typically involves a level of simplification for practical reasons. Those simplifications, combined with the limitations in describing complex phenomena of thermal buoyancy and heat transfer, require a verification of the coherency of the results obtained from the computational models. In this process, one of the approaches used is the code-to-code comparison in order to ensure consistency between tools [36]. In this respect, IES VE results are compared against those obtained from a FLOVENT. Both software tools claim to have been gone through validation procedures against a number of standards by several institutions; still, the code-to-code verification is performed here to better elaborate on boundaries, limitations and differences.

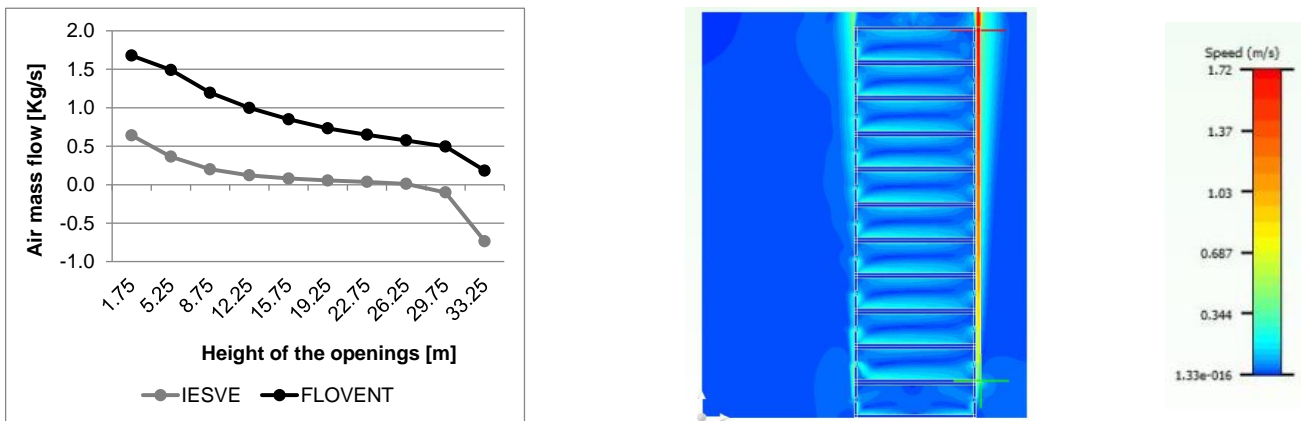


Figure 4 – Net air mass flow induced on the floors of IES VE and FLOVENT models (right) and view of the CFD results (left)

In this test, a steady state condition of an outside temperature of 25°C was set in both software and internal gains of 30W/m² were applied in the office rooms as the unique heat source in the models. Therefore, a customised weather file, without wind speed and solar radiation, was fed into IES VE. Although results indicate similar trends of airflow across all floors, IES VE seems to underestimate induced airflow rates in comparison to CFD, as shown in Figure 4. Based on the knowledge base of both software modelling and calculation available, several attempts have been made to decrease the flow range difference. One of the concerns in the DSF modelling, raised by Dickson [37] and by Kim and Park [38], is about the convective heat transfer coefficients used and the algorithm for their calculation. Dickson [37] highlighted that, although in building energy simulation the ‘Alamdari & Hammond’ calculation is the most indicated for DSF buildings, it is still not fully suitable to narrow cavities. Such an approach underestimates the heat transfer to the air, subsequently causing less buoyant force to drive air through the channel. Kim and Park [38] added that the literature values of those coefficients are empirically driven for general cases and they can significantly vary according to system parameters, such as DSF configuration and location. Therefore, different convective heat transfer coefficients combined with available algorithms of calculation have been tried.

A further test addressed the divisions within the cavity. A recommendation against using too many zones is given by IES VE, as it would introduce an artificial resistance to the flow field because the software algorithm does not model stratification explicitly. The discharge coefficient (D_c) of 0.62 is used to calculate the airflow on the model opening [39] but CIBSE [40] stated that since the shape of the chimney is very different from a sharp-edged opening, its discharge coefficient may exceed this value. Thus, four different scenarios adjusting the percentage of equivalent areas (120, 150, 175 and 250% respectively) for the openings at the bottom, at the top and within the cavity have been performed.

Additionally, different opening categories such as ‘duct’, ‘hole’, ‘grill’ and different exposure types within IES have also all been tested. Furthermore, in order to verify whether the horizontal divisions in the cavity were worsening the artificial resistance to the ascendant air flow, four models with fewer partitions in the cavity have been compared in both software tools. Eventually, vertical partitions, beyond the horizontal ones, have also been applied to the IES VE model. Nonetheless, none of these tests led to significant changes in the airflow prediction. The IES VE airflow range remained consistently and permanently lower than that shown by FLOVENT. In terms of judging which prediction is more accurate, Dickson [37] suggests to favour CFD calculations as they are obtained by solving the fluid mechanics fundamental equations.

As a conclusion, IES VE has proven to be remarkably consistent across a fair number of changes in parameters and settings. Whether IES VE makes a set of mathematical assumptions that reduce the predicted flow or FLOVENT overestimates the actual airflow cannot be univocally vouched for without experimental data. Nevertheless, and for the sake of this study, the underestimating airflow prediction by IES VE is a conservative assumption and represents a prudent approach.

4. Results and Discussion

Results are provided for all six scenarios which were devised and assessed for this study. Figure 5 shows findings for the three London cases. On the left, data points related to indoor conditions are plotted in an adaptive comfort chart. The data refer to the 4th DSF level (L4 floor) of the building model, as the representation of the average floor seemed to be the most appropriate. It is worth highlighting that adaptive comfort charts are significant only within a specific range of prevailing mean outdoor temperatures. Due to the colder climates in London, several times a year the prevailing mean outdoor temperature fell outside this range. To address such an issue for those times in the year the adaptive comfort approach has been enriched with comfortable winter indoor conditions according to CIBSE Environmental Design Guide [41]. In this respect, comfortable hours for the London cases are distinguished between those related to the adaptive comfort (AC) and those related to the Environmental Design (ED). Data points are classified with a colour legend, according to the season they belong to. Such a representation shows in which seasons the DSF performs better and whether significant seasonal trends can be observed.

Yearly totals in terms of comfortable and uncomfortable occupied hours (both due to too hot/too cold conditions) are plotted in Figure 5 (right) for each of the floors of the building model. As shown in those graphs, no significant variation is observed across different orientations and different floors. This can be due to the prevailing DSF mode of operation in temperate conditions, i.e. the thermal buffer behaviour. In such a case, certain outside conditions, i.e. wind, have lower influence on the occupied spaces as the DSF acts as a barrier to reduce heat losses through the building’s inner skin.

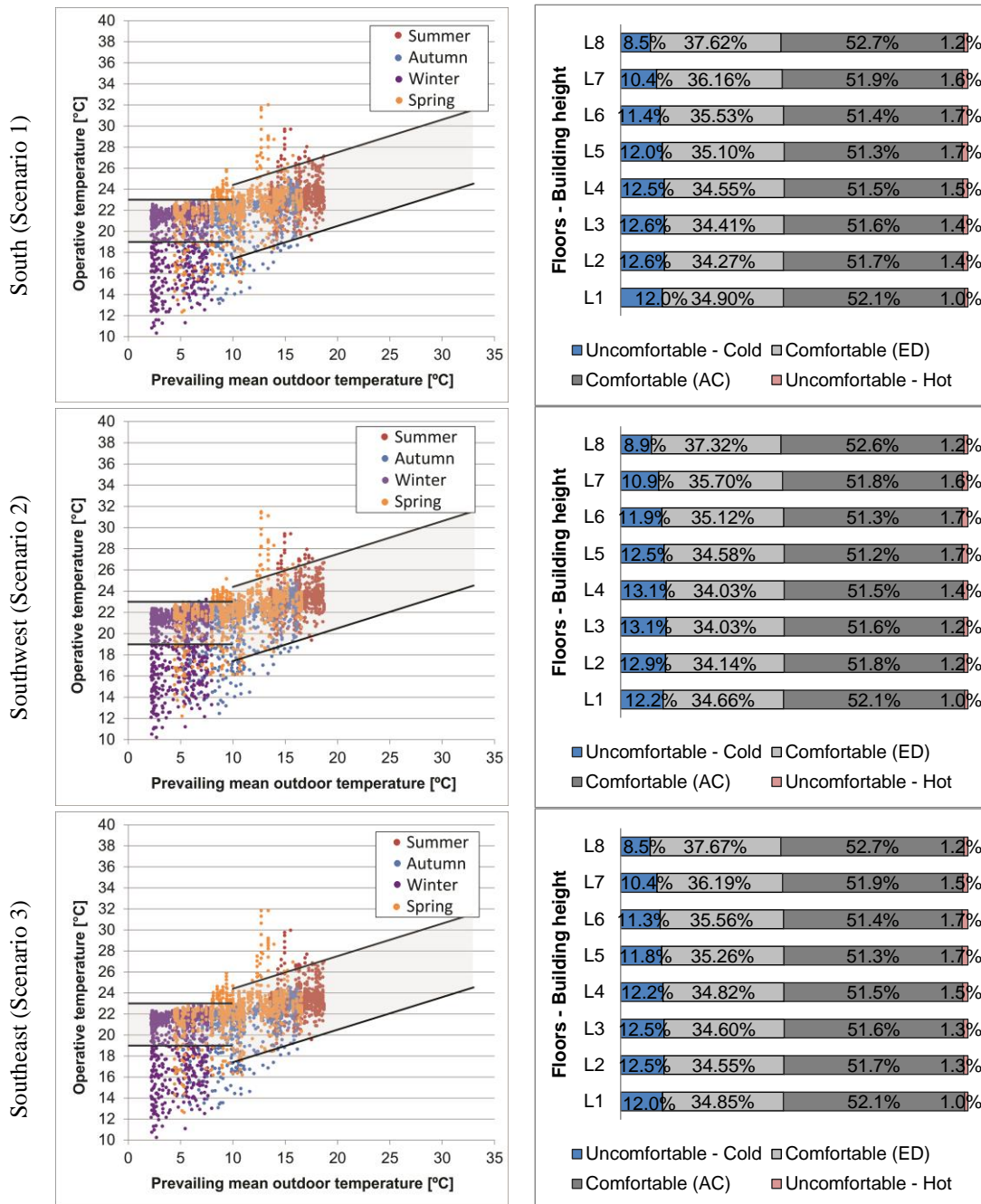


Figure 5 - Results for London

Furthermore, in London, prevailing winds often hit the DSF, which then is on the windward side of the buildings. Such a combination of prevailing wind direction and DSF orientation is the least favourable to exploit the DSF natural ventilation potential [42, 43]. Nonetheless, the DSF in London shows a very promising energy saving potential due to an advantageous combination of its thermal buffer mode and natural ventilation potential in that specific climate.

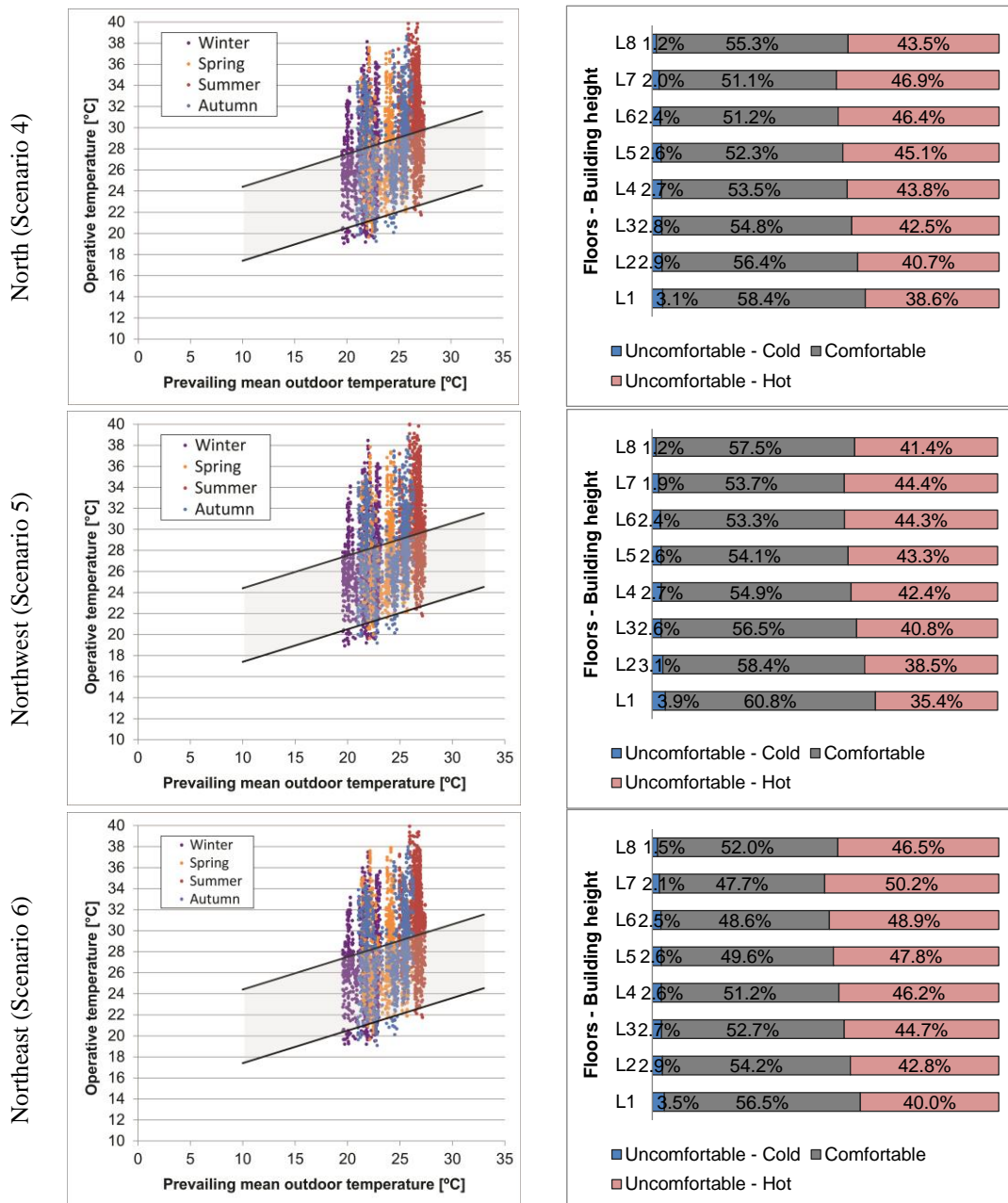


Figure 6 - Results for Rio de Janeiro

Figure 6 presents the same type of findings for the three orientations in Rio de Janeiro. For these cases, all the yearly data points could be plotted within the standard adaptive comfort interval since the prevailing mean outdoor temperature never falls outside the significance range for those charts. As in the London cases, also in the tropical climate the passive strategies due to the DSF can offer comfortable indoor conditions for a very significant portion of the occupied hours in a year, with a peak of 60.8% in the Northwest orientation (Scenario 5). It is worth noting that such a numerical value matches extremely closely what the psychometric chart suggested in terms of comfortable hours thanks to natural ventilation strategies.

The graphs show that in Rio de Janeiro, there is a higher variability of the thermal performance in the model. The higher share of comfortable hours is always found on the lowest floors equipped with the DSF and it constantly decreases throughout upper floors to eventually slightly increase again on the last floor (this is also true for London but to a lesser extent). On the lower floor the temperature gradient has its highest value, thus maximising the thermal stack effect [43, 44]. The last floor, however, shows an inversion of such a phenomenon, with more comfortable hours than the floor below it, and this is perhaps due to a combined effect of the residual chimney of the DSF and higher wind speeds that occur at that height of the building. This is consistent with previous findings of naturally ventilated DSF buildings, in which an adequate set of openings force fresh air from outdoor to enter indoor via the windows of the opposite façade to then pass through the occupied spaces and enhance the capability to extract the heat into the cavity [5, 45]. Furthermore, the wind rose for this city indicates that prevailing winds come from the opposite side to the DSF.

Thus, the wind pressures reinforces the cavity stack effect and cooler air is taken from outside through the user room, improving the overall building thermal performance in warmer climates.

5. Conclusions and further research

DSF projects are many around the world, and applications in both new and refurbished buildings are increasingly gaining momentum. Although much research has been done on the operational behaviour of the DSF, little is still known about its flexibility and capability to adapt to extremely different climates. In this respect this research has represented a thorough attempt at filling such a gap. A building equipped with a specific DSF configuration has been analysed in two different climatic zones, i.e. tropical (Rio de Janeiro) and temperate (London).

Results show that for significant portions of the year, the DSF can provide comfortable indoor conditions without any need for mechanical heating or cooling, hence no excess load on energy use. This outcome highlights how often energy is wasted to heat and cool buildings for which passive measures could be successfully put in place. Best results in London peak at 85% of comfortable indoor conditions achievable thanks to the DSF, whereas for Rio such a value is as high as 61%. More variability of the DSF performance is observed in Rio and the reason is twofold. Firstly, in Rio, the DSF cavity is always open and therefore more influenced by the surrounding environment. Secondly, due to more favourable prevailing wind speeds and direction, the wind plays a major role in the Rio cases, and this reinforces the need for a careful analysis of the surrounding environment and climate before a DSF is put in place.

Findings from this study are very promising towards a much greater exploitation of the DSF as passive design strategy. However, this study is chiefly based on simulations and this represents its main limitation. Furthermore, it is still not clear how well BEEM tools can model the complex thermal phenomena happening in a DSF. Although a code-to-code model calibration was carried out, more work is needed to increase the reliability of simulation results. Finally, field monitoring of DSF buildings and/or experimental data would greatly help confirm the very promising energy saving potential assessed in this paper.

Future research could address any of these aspects and could also take into account more parameters for a successful DSF design, such as different glazing types and alternative shading systems. Eventually, expanding the study to a bigger selection of different climates, could examine whether the flexible behaviour of a DSF continues to lead to successful deployments of passive strategies.

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